Aalto University
School of Business

CARBON LEAKAGE

Are Carbon Tariffs a Necessary Tool in Climate Policy?

Master's Thesis
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Abstract of master's thesis

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Abstract

In absence of binding global agreements on climate policy some regions like the European Union have decided to take unilateral actions to reduce their greenhouse gas emissions. These unilateral actions have raised carbon leakage as an important policy issue to be addressed. Carbon leakage means that emission reductions in one region may be offset at least partially by emission increases in the rest of the world as fossil fuel prices fall and domestic companies lose their market shares.

This thesis will review the literature concerning the magnitude of the carbon leakage effects and measures to prevent it. The results of these studies are assessed in light of an optimal carbon tariff and tax model introduced by Hoel (1996). The work will provide an overview on estimates of the scale of carbon leakage rate, in addition to an assessment of carbon tariffs and current policy measures as tools to prevent leakage.

The findings suggest that carbon leakage is probably a remarkable threat only in certain energy-intensive sectors most exposed to foreign competition. Carbon tariffs or other border adjustments would therefore be limited in scope as a tool of climate policy. Their cost-effectiveness in global emission policy is doubtful, as they would mostly shift the cost burden from developed to developing world, rather than reducing emissions globally. This implies that tariffs would not be a necessary tool in unilateral climate policy. However, the same critique applies to the current measures in the EU as well. Also, the free permit allocation system currently in use is probably too lax, and thus produces effects contrary to the goals of emission policy while providing little protection for domestic industries.

Keywords carbon leakage, border carbon adjustments, carbon tariffs, climate change policy, carbon taxes, climate economics

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Tiivistelmä

Sitovien globaalien ilmastosopimusten puuttuessa Euroopan unioni joidenkin muiden alueiden ohella on ottanut käyttöön omia yksipuolisia ilmastopoliittisia keinojaan, kuten EU:n päästökauppajärjestelmän. Nämä toimet ovat kuitenkin herättäneet huolen niin sanotusta hiilivuodosta, eli päästöjen karkaamisesta ulkomaille, mikäli niitä rajoitetaan yksipuolisilla politiikkatoimenpiteillä. Hiilivuotoa voi tapahtua, jos fossiilisten polttoaineiden hinnan lasku kannustaa käyttämään niitä enemmän muualla maailmassa, tai jos kotimainen energiaintensiivinen teollisuus menettää markkinaosuuksiaan hiilisääntelyn seurauksena.

Tämä tutkielma käy läpi, miten suureksi hiilivuoto on aikaisemmissa tutkimuksissa arvioitu, ja mitä toimenpiteitä sen ehkäisemiseksi on ehdotettu. Tuloksia arvioidaan käyttämällä lähtökohtana Michael Hoelin (1996) mallia optimaalisten hiilitullien ja hiiliverodifferentiaation määrittelyyn. Työ tarjoaa yleiskatsauksen arvioista hiilivuotoasteen suuruusluokalle, sekä arviointia hiilitulleista ja nykyisistä politiikkatoimenpiteistä hiilivuodon ehkäisemiseksi.

Tulosten perusteella hiilivuoto on merkittävä uhka vain tietyillä energiaintensiivisillä aloilla, jotka ovat alttiita ulkomaiselle kilpailulle. Hiilitullit ja muut rajaverot olisivat siten varsin rajallinen työkalu ilmastopolitiikassa. Niiden kustannustehokkuus globaalilla tasolla ilmastopoliittisena toimenpiteenä olisi heikohko, sillä niiden vaikutus olisi ennemminkin ilmastopolitiikan kustannustaakan siirtyminen teollisuusmaista kehitysmaihin kuin päästöjen väheneminen globaalilla tasolla. Sama kritiikki kuitenkin koskee merkittävässä määrin myös nykyisten kaltaisia politiikkatoimenpiteitä EU:ssa. Nykyjärjestelmä, jossa päästöoikeuksia jaetaan ilmaiseksi on todennäköisesti myös liian löyhä, ja toimii siten ilmastopolitiikan tavoitteiden vastaisesti, tuottamatta kuitenkaan merkittävää hyötyä EU:n oman tuotannon suojelemiseksi.

Avainsanat hiilivuoto, hiilitullit, ilmastopolitiikka, hiilivero, ilmastotaloustiede

Contents

Symbols and abbreviations

Hoel's model:

c: Consumption vector

c_0: Domestic consumption of fossil fuels

E: Environmental costs

e: Foreign emissions

I: Household income

m: Net imports

p: Price

U: Utility

v: domestic production

W: Welfare

x: Stock of capital goods

y: domestic output vector

z: Total emissions

Abbreviations

ARE: Abatement Resource Effect

CES: Constant elasticity of substitution

CET: Constant elasticity of transformation

CGE: Computable General Equilibrium

CO_2: Carbon dioxide

EKC: Environmental Kuznets-Curve

EU ETS: European Union Emissions Trading Scheme

FBA: Full Border Adjustment

H-O: Heckscher-Ohlin (assumption)

IOE: Input-Output Effect

OBR: Output-based Rebate

PHH: Pollution Haven Hypothesis

WTO: World Trade Organization

1 Introduction

Reduction of greenhouse gas (GHG) emissions is one of the largest challenges today in international politics. Since global warming is considered to be mostly driven by carbon-dioxide (CO_2) emitted by burning of fossil fuels, the most important way to cut emissions is abatement of fossil fuel consumption. However, countries have this far disagreed about the relative levels of abatement between countries, and, despite the recent Paris Agreement, no binding agreements have been made on global level. Though many areas have adopted unilateral emission reduction schemes, these efforts have been dampened by fears of a phenomenon known as carbon leakage.

Carbon leakage refers to a situation where policy efforts to reduce carbon dioxide emissions in a specific region increase emissions in other regions. The definition looks neat, but the phenomenon is actually immensely complex: carbon leakage basically covers all changes in emissions in all sectors and regions not directly affected by the regulation in question. Because only the aggregate amount of emissions on a global level matters in the case of CO_2 emissions, a reduction of emissions in one part of the world is of no use if it will be offset by an increase somewhere else. Since no binding global agreements on reducing emissions has been done, countries that adopt emissions limiting policies need to ensure in their policy design that a large part of their reductions will not simply be offset by increases elsewhere. Therefore carbon leakage has been and will be an important issue for unilateral climate policy.

Even though leakage is clearly deemed as an important issue, it is not clear how it should be tackled in policy-making. The existence of the phenomenon might serve as an excuse to do nothing, or it may cause political pressures to hand undeserved benefits to certain interest groups. The European Union has tried to prevent carbon leakage within its EU Emissions Trading Scheme (EU ETS) by allocating larger shares of free emission allocations to those sectors deemed most vulnerable to leakage.

Additionally, Finland has attempted to ensure competitiveness of its own energy-intensive industries by rebating energy taxes. According to study by VATT Institute for Economic Research, these rebates of energy taxes have not been an effective tool to enhance competitiveness of the firms in those sectors Harju et al., 2016, even though rebates have risen to over €200 million annually. The result suggests that inefficient tools for leakage prevention may be both economically wasteful and counterproductive to the goals of climate policy. This highlights the importance of a careful policy design to counter carbon leakage, both from environmental and economic point of view.

In absence of global price for GHG emissions, "carbon tariffs" have been proposed as the second-best option to ensure effectiveness of climate policies, and protect the competitiveness of emission-intensive industries in regulating regions. However, tariffs too are a problematic policy tool to adopt, since they may contradict the rules of international trade agreements, and might be seen as disguised protectionism.

In this thesis I will review the literature concerning the carbon leakage and strategies to mitigate it. The next chapter will provide an overview of the most relevant terms and concepts related to carbon leakage, and introduce the mechanisms that cause the leakage to occur. In the third chapter I will introduce Michael Hoel's (1996) model that analytically shows a solution to optimal carbon tax and tariff levels. Using this model as a starting point, I will review the estimates for the magnitude of carbon leakage found in studies in chapter four, and discuss different strategies to mitigate leakage in chapter five.

2 Key concepts and definitions

In this section I will introduce and define some key concepts related to carbon leakage and climate change economics.

2.1 Carbon dioxide emissions as a global "public bad"

Nordhaus (1991) characterized greenhouse gases that give rise to global warming "the granddaddy of all public goods", as the effects of GHG emissions spread all over the world and indefinitely to the future, while causing serious and unpredictable damages. The use of fossil fuels, and other GHG emitting goods and resources, are not at an efficient level because of these climate externalities they produce. Consumers of fossil fuels do not need to accommodate the harms to climate to their own costs, therefore a government intervention is required to limit the emissions. In this thesis, when writing about emissions, I will use carbon dioxide and GHG interchangeably, even though there are other significant GHGs as well, like nitrous oxides and methane. However, the same principles can be applied these other GHGs when their global warming potential is converted to "CO_2 equivalence".

In an economist's perfect world the emissions would be efficiently curbed by a Pigouvian[1] global carbon tax or other kind of pricing mechanism for emissions, preferably set to tax GHG emissions directly at their source. The tax would set price on carbon and thus reduce emissions to socially desirable level while allowing efficient allocation of resources. However, there is no global government to place the tax, nor a binding international agreement to enforce nation states to do so. This leaves the policy measures to individual countries or groups of countries. But since the externality is global in its nature and demand-based measures may increase

[1] A tax equivalent to the social cost of a negative externality, originally proposed by Arthur C. Pigou in the book *The Economics of Welfare* in 1920 (Pigou, 2013).

other countries' incentives to use fossil fuels, unilateral measures are not necessarily effective.

2.2 Carbon leakage: the definition

Intergovernmental Panel for Climate Change (IPCC) defines carbon leakage as "the increase in CO2 emissions outside the countries taking domestic mitigation action divided by the reduction in the emissions of these countries" (Barker et al., 2007). The term itself was probably first coined by Felder and Rutherford, 1993, though the concept of unintended consequences of environmental policies has been discussed before. The basic principle of leakage is widely shared in the literature but there are some nuance differences in how broad sense the term is used between different studies. For example, B. Copeland and M. Taylor (2005) define carbon leakage as the pure substitution effect of price change in a fossil fuel price after unilateral emission reductions. This definition implies that leakage only refers to those changes in emissions that occur through price changes in fossil fuels. In a broader sense, carbon leakage includes all changes in foreign emissions caused by domestic efforts to reduce carbon dioxide emissions, or even changes in emissions in sectors other than the regulated ones.

There are also notions of 'negative leakage', i.e. situation where emissions abroad actually decrease rather than increase as a result of abatement policy. Inclusion of negative leakage and leakage to other domestic sectors in the term means that it actually refers to all changes in emissions in any period by any actor other than those to whom the policy is targeted. This is of course what we want to know when we evaluate a policy: its actual side-effects. However, for analytical purposes the definition often needs to be narrowed down. For example, If there are other remarkable mechanisms for emission changes, they are excluded. The point of this is to demonstrate that it is important to distinguish between the term's use in describing the phenomenon as a whole and the use of the term in a specific study.

2.3 Free riding

The concept of carbon leakage is related to but partly separate from the problem of free-riding in the climate policy. A country is a free-rider if it stays out of a climate agreement but gets to enjoy most of the benefits of the policy without paying any of the costs associated with the GHG emissions. Carbon leakage amplifies this problem. When goods can be traded across borders, a free riding country does not only get to enjoy the benefits of reduced emissions, but also gains additional economic benefits as its industries may gain competitive advantages over those of regulated countries.

2.4 The main mechanisms of carbon leakage

Two main mechanisms for carbon leakage can be distinguished. First is the short run effect that follows from decreased fossil fuel prices: as demand for fossil fuels decreases in the region that has adopted tighter regulations, price of the fuels drops outside the region and their use intensifies. Second is the production relocation effect: when new controls for emissions are adopted, investment in carbon-intensive production becomes relatively more profitable in countries with laxer regulations, which may result in more investments in those countries (M. Babiker, 2005). The research has mainly focused on the first of these effects, as the immediate short-run effects are easier to model than more complicated longer-run investment location choices.

Another way to distinguish the two different main mechanisms for carbon leakage a general equilibrium setting is to divide the effects to energy and non-energy market channels (Burniaux and Joaquim Oliveira Martins, 2012). In non-energy markets channel carbon abatement leads to higher production costs in energy-intensive industries. If these industries lose their market share as a result of these higher costs, production intensifies in countries without abatement policies, which again leads to higher emissions these countries. The intensity of this mechanism depends on trade substitution elasticities (i.e. Armington elasticities): larger elasticities mean price changes have greater effects on market shares. In addition to direct effects in goods market, non-energy markets leakage may also happen through shifts in foreign direct investment to non-abatement countries. (Burniaux and Joaquim Oliveira Martins, 2012)

The energy markets channel operates through fall in international prices of fossil fuels caused by decreased demand in abating countries. This fall would intensify energy demand and emissions in non-abatement countries. The structure of the international energy markets is a significant factor for the size and scope of this effect. There are differences in the structure of international oil and coal markets. Whereas oil is usually considered fairly homogenous good, integration of global coal market is much more debatable. (Burniaux and Joaquim Oliveira Martins, 2012)

B. Copeland and M. Taylor (2005) divide unilateral emission cuts' effects to a country outside the reduction scheme to free-riding, carbon-leakage and bootstrapping effects. In their analysis the best solution for climate policy depends on relative strengths of these effects. The free-rider effect is the pure strategic effect of the foreign emission restrictions with the price of fossil fuel staying constant. Carbon leakage is the substitution effect of the following price change in the fossil fuel. The third effect that the authors call bootstrapping is the income effect: when a country's income rises as a result of former two effects, its consumption of environmental quality rises and thus emissions drop. All three of these effects can be considered to be mechanisms that contribute to the overall level of carbon leakage, although in the authors' model carbon leakage is only considered as one of them.

2.4.1 Negative leakage and other mechanisms

In addition to the main effects described above, literature has identified several other mechanisms that may contribute to the carbon leakage, in both positive and negative ways. The effects that decrease emissions also abroad are called, as mentioned before, "negative leakage" effects. For example, setting emission restrictions in one country may accelerate technological change that will make cleaner and cheaper technologies available in unregulated countries as well. Though negative leakage is not carbon leakage in the term's original meaning, it is important to take them into account when evaluating the effects of unilateral policies. If negative leakage effects are ignored, estimates of leakage rate will be overestimated.

J Oliveira Martins (1996) suggested that there may exist mechanisms that cause negative leakage rates in some cases. In Oliveira Martin's analysis these effects were caused by the larger relative fall in price of oil in comparison with coal. This would result to shift in energy use from coal to oil. Since oil's CO2-emissions per energy output are significantly coal's, this could reduce emissions to some extent. This result shows that negative leakage may occur even through the main leakage mechanisms.

B. Copeland and M. Taylor (2005) showed that endogenous policy in unregulated countries may decrease emissions. There is an observed link between increased income and environmental protection within countries as discussed earlier. Therefore countries may adopt stricter pollution-control policies if their income rises as a result of carbon leakage. Endogenous policy change may also arise from other factors than rising income, for example, adoption of unilateral abatement regulation may increase political pressure in other countries to adopt their own emissions reduction policies.

However, this kind of evolution of political processes is pretty hard to capture via economic modelling.

Endogenous technological change may also have a negative leakage effect. A carbon tax may accelerate development of emission decreasing technologies. This is probably part of the intended consequences of the policy scheme in the first place, but these technological changes do not necessarily only decrease emissions in the regulated sector but can create spillovers that decrease emissions in other sectors and countries as well (for example Di Maria and Smulders, 2004; Gerlagh and Kuik, 2007). Di Maria and Van der Werf (2008) described in their theoretical model an "induced-technology effect". Changes in relative prices caused by carbon regulation also shift the incentives to innovate to a direction that decreases carbon leakage.

A theoretical paper by Fullerton, Karney, and Baylis (2011) presents an Abatement Resource Effect (ARE). This effect occurs when price on carbon induces firms to abate carbon per unit output by using more clean inputs. This draws resources from other sectors, which in turn reduces their output, and thus emissions. In other words, carbon leakage may be reduced, if abatement draws factors away from other carbon-intensive production activities. Three conditions need to be fulfilled in order for ARE to occur. Goods cannot be perfect substitutes, taxed sector needs to be able to substitute some of its carbon-intensive inputs to other inputs, and labor or capital needs to be mobile between sectors (Elliott and Fullerton, 2014). Since capital and labor are usually assumed immobile between regions in computable general equilibrium (CGE) models by which carbon leakage is most often assessed, they cannot capture ARE. Another negative leakage effect identified by Elliott and Fullerton (2014) is the “input-output effect” (IOE). If a good is used as an intermediate output of another good, that other good may become more expensive as well after carbon tax is applied to the intermediate good. This could reduce production of the final good and emissions associated with it too.

Though some authors have incorporated these effects into their models, it is extremely challenging to try to model things like speed and direction of technological change or political decision-making in models that try to quantitatively estimate the magnitude of carbon leakage. Some authors argue that the scope of carbon leakage tends to be overestimated in the studies because negative leakage effects are not included in analyses. On the other hand, it is also possible that the extent has been underestimated, since models do not fully capture possible changes in investment flows either.

2.5 Leakage rate

Carbon leakage rate is the ratio between total increase in CO_2 emissions in countries that did not adopt abatement measures, and total abatement in countries that did. For example, if a country adopts a carbon abatement policy that decreases its emissions by 100 million tons and, as a result, emissions in rest of the world increase by 40 million tons, the leakage rate is 40% (Paltsev, 2001). Though it seems that many models estimate the carbon leakage rate to be around 5 to 30 percent (for example Paltsev, 2001; Böhringer and Löschel, 2002; M. H. Babiker and Rutherford, 2005; Ho, Morgenstern, and Shih, 2008), the estimates depend heavily on key determinants and some models with certain assumptions have led to results where carbon leakage would be over 100% (e.g. M. Babiker, 2005). I will provide a closer look at the estimates of the leakage rate in chapter 4.

Though simple as concept, the carbon leakage rate is also immensely difficult to predict. The effects result from complex interactions between global energy and non-energy markets. Direct empirical evidence is impossible to obtain for regulation not yet adopted, and extremely hard to identify for already adopted regulation schemes. Therefore measurement of the magnitude of carbon leakage has mainly relied on computable models. Models are typically computable general equilibrium models with multiple regions and multiple sectors where prices determine to a large extent global supply and demand. Trade flows respond to relative prices changed by unilateral carbon regulation and as a result carbon emissions change in the rest of the world. Partly empirical data from input-output tables is combined with assumptions on market structure and elasticities to compute how world economy adjusts to adopted regulation (Böhringer, J. Carbone, and Rutherford, 2016).

2.6 Pollution Haven hypothesis

The pollution haven hypothesis (PHH) claims that differences in environmental protection regulation provide a competitive advantage in pollutant industries to those countries with laxer regulation (Cole, 2004). This would lead to relocation of those industries from rich countries with stricter regulations to developing countries with less or no regulation. The implication of this is that countries set their environmental protection levels lower than would be socially optimal to promote investment or exports. It is thus a concept closely related to carbon leakage. In fact, the industry relocation mechanism of carbon leakage can be understood as a special case of the pollution haven hypothesis.

The PHH is often linked with environmental Kuznets-curve (EKC). EKC states that there is an inverted U-shaped relationship between per-capita income and environmental degradation. PHH challenges the view that existence of EKC would mean decrease in total pollution after a country's per-capita income reaches a certain level, but rather implies that the pollution is outsourced from rich countries to poor ones. (Cole, 2004)

Although carbon leakage can be understood as a special case of wider PHH, effects of CO_2-emissions are quite different from most other pollutants. Other pollutants are local or regional bads: contaminated ground water only affects people who use that particular source of water and acid rains caused by air pollutants affect only limited – though large – area. However, from a location of production point of view, CO_2-emissions are bad only on global level. Effects of global warming may differ across regions but the location of where emissions are produced does not make any difference, only total amount of emissions globally matters.

There is empirical evidence on the existence of the Environmental Kuznets-curve, but its connection with Pollution Haven Hypothesis seems vague. Several studies (M. S. Taylor, Antweiler, and B. R. Copeland, 2001, Grossman and Krueger, 1995 and Grossman and Krueger, 1996) suggest that there is a link between income gains and environmental protection (though the link does not seem to be inverse U-shaped for all pollutants). For example M. S. Taylor, Antweiler, and B. R. Copeland (2001) and Harbaugh, Levinson, and Wilson (2002) find little evidence for PHH. Cole (2004) states that evidence on the PHH has been mixed. Part of the results imply that free trade may be harmful to the environment, but the result comes mainly from the scale effect: increased economic activity in itself increases pollution. Evidence of pollution shifting from developed to developing countries is quite weak.

Though no clear evidence of PHH on other pollutants has been found, carbon-dioxide might be a different case. Pollution control costs for other pollutants may be so small that they do not have significant impacts on location of industries. Reduction of carbon-dioxide emissions is probably costlier: some improvements can be made by enhancing energy efficiency but radical reductions require change in primary energy sources.

2.7 The Green Paradox

The Green Paradox refers to a situation where a policy that is designed to reduce emissions leads to an increase of emissions instead. The current debate around the phenomenon was first started by Sinn (2008). He focused the incentives of fossil fuel owners to sell their stocks before they lose their value as a consequence of climate change policies, though the term has more recently come to refer to emissions-increasing consequences of climate policies in a broader sense. In some papers a leakage rate of over 100% is defined as the Green paradox (e.g. Eichner and Pethig, 2011).

The optimal extraction rate of scarce natural resources, such as fossil fuels, is theoretically the same for both owners of the resources and the society as whole if there is no extraction costs. This was originally shown by Hotelling (1931). CO_2 emissions violate this Hotelling rule because they produce a major externality for fossil fuel extraction. Therefore socially optimal extraction rate requires government intervention. However, demand-reducing policies for fossil fuel consumption have two countervailing effects on current extraction rate: they reduce incentives to extract today by lowering prices, but they also increase the incentive because anticipated demand in the future decreases. If the former of these effects is larger, the policy actually increases current emissions. If the producers now expect that the fossil fuel will be replaced by clean fuel in the future, they will pump all the fuel if the marginal cost of extraction is zero. If the interest rate remains unchanged, the price will be lower at all times before the point of time when producers expect replacement to happen Sinn, 2008. In the context of carbon leakage this mechanism could also be understood as intertemporal carbon leakage (Jensen et al., 2015).

If the Green Paradox is a real concern, the expectations of future carbon regulations become truly important. The price of carbon should be set at a high level first, and then lowered if necessary. Otherwise the expectations of tighter regulations in the future could incentivize suppliers to sell their fossil fuels stocks as more quickly than otherwise (Eichner and Pethig, 2011). This kind of development is not usually considered in the estimates of carbon leakage, but it may be relevant when climate policy measures are designed.

2.8 Pollution and international trade

The debate over carbon leakage is part of the wider discussions on the relationship between environment and international trade. Both climate policy and trade liberalization are goals of international policy that should generally enhance global welfare, but in practical level are difficult to agree about. They are also sometimes seen as somewhat conflicting policy goals; international free trade can be argued to "cause" the carbon leakage. Under total autarky production could not move from one country to another as a result of abatement policies because the goods or resources could not move between different countries. However, in practice the linkage between freer trade and pollution is much more complex. For example, Kuik and Gerlagh (2003) studied effects of increasing trade liberalization to carbon leakage rates. Due to implementation of Uruguay round's agreements, international trade has been liberalized after the implementation of the Kyoto Protocol. They found that, under plausible assumptions, tariff reductions indeed increase the rate of carbon leakage. These increases however can be offset with smaller costs than the additional benefits of freer trade by the authors' estimation.

There are several channels through which trade affects pollutions levels. Grossman and Krueger (1991) broke the relationship between environment and trade into three components. The scale effect increases pollution due to increased economic growth as a result of trade. If trade enhances economic growth, which in turn increases demand for energy-intensive production, CO_2 emissions rise as more fossil fuels are used in production. The technique effect refers to the changing of production techniques as a result of liberalized trade. For example, better access to environment-friendly technologies may be achieved in less developed countries when foreign investment restrictions are relaxed. And finally, the composition effect is the changes in composition of production due to specialization in activities where countries enjoy comparative advantage.

3 Theoretical framework

3.1 Hoel's model

In this chapter I will introduce Michael Hoel's model (1996), with which Hoel analyzed whether carbon taxes should be differentiated between different sectors in order to mitigate possible carbon leakage and ensure effectiveness of the policy. Hoel builds on earlier work by Markusen (1975), and generalizes Markusen's case of a two-sector, two-region model. Hoel's main argument is that differentiation between sectors is not advisable if carbon tariffs can be implemented. If tariffs are excluded from the instruments of climate policy for some reason, differentiation becomes optimal. In the following subsection I will show how the model works, and the analytical reasoning behind Hoel's arguments.

3.1.1 Consumption and production pattern

The domestic consumption vector in the model is $c = (c_0, c_1, ...c_n)$. The vector represents the consumption choices of goods by a representative consumer in the model. The goods in the model are indexed so that the first $1 + \eta(\leq n)$ goods are traded goods, the rest being non-tradables. Welfare in the model is the function of domestic consumption of fossil fuels (c_0), and other products (c_1 to c_n). Domestic utility function is thus written as

$$W = U(c) - E(z) \tag{1}$$

where $E(z)$ is the environmental cost of emissions from all countries. In other words, domestic welfare grows only when products are consumed within the country, while CO_2 emissions lower welfare also when they are produced abroad. In a socially optimal situation the utility from consumption in home country will be maximized with harm from global emissions taken into account.

Total emissions (z) consist of domestic consumption of fossil fuels (c_0), domestic use of fossil fuels as production inputs (v), and foreign emissions (e):

$$z = c_0 + v + e. \tag{2}$$

The reduction in domestic components of the emissions is the main intention of a carbon tax, while carbon leakage would increase foreign emissions.

The vector m denotes net imports, so the domestic net output is represented by vector $y \equiv c - m$. Negative components of m denote exports. Since non-traded goods are not imported, $m_i = 0$ and domestic output equals consumption ($y_i = c_i$). For each value of production input v, there is a set of net outputs of all goods. These are important to include explicitly in the model, since the fossil fuel inputs affect the environmental impact of production. Output possibilities are specified by a transformation function of general type $F(y, v) \leq 0$, where F is increasing in each y_i. The derivative F_v is smaller than zero as long as fuel input is lower than would be efficient in absence of environmental externalities (i.e. increase in fuel use will increase the economy's output). Efficiency implies that $F(y, v) = 0$ (output is at the production frontier) and $y = c - m$ (domestic net output equals consumption minus net imports), so

$$F(c - m, v) = 0 \tag{3}$$

describes efficient combinations of net outputs and fossil fuel inputs in production.

Balanced trade is defined as the current account of zero, and trade is assumed to be balanced. Therefore the monetary sum of imports minus exports needs to equal zero:

$$p(m)m = \sum_{i \leq \eta} p_i(m)m_i = 0. \tag{4}$$

Terms $p(m) = (p_0(m), p_1(m), ..., p_\eta(m)$ are international prices of traded goods. These prices can be changed through changes in net imports.

The framework allows capital movements. If a given physical stock of capital is denoted by x_k, and the use of this capital in production by v_k, net output can be written as $y_k = x_k - v_k$. Since $y_k = c_k - m_k$, we get $v_k + c_k = x_k + m_k$. This means that more capital must be imported when use of capital is increased in domestic production or consumption.

Foreign carbon emissions are also assumed to depend on the net imports. The model only considers carbon leakage that occurs as a direct consequence of relative price changes following introduction of carbon tax. It does not capture for example industry relocation effects or the structure of international energy markets. Therefore foreign emissions can be written simply as

$$e = e(m) = f(p(m)). \tag{5}$$

In the simple case, importing energy intensive goods raises their international prices and foreign production ($\partial f / \partial p_j > 0$), and thus increases emissions. Whereas the opposite is usually true for goods which use little or no fossil fuels, since demand for clean products shifts foreign production away from the energy intensive goods.

Hoel defines the social optimum as the vector (c, m, v) which maximizes welfare (1), subject to conditions (2)-(5) presented above, and $m_j = 0$ for all non-traded goods. Or shortly as a combination of domestic consumption, net imports and domestic fossil fuel inputs that has the highest utility when harm from global emissions is taken into account. Following conditions can be calculated for a social optimum.

First, marginal rate of substitution (MRS) needs to equal marginal rate of transformation (MRT), with environmental externality (E') included in the MRS. This is the standard requirement of efficiency. The marginal environmental cost fossil fuel use needs to be included in the MRS between fuel use and consumption of other goods to capture the marginal loss of welfare from emission increase:

$$\frac{U_0 - E'}{U_i} = \frac{F_0}{F_i}, \quad i = 1, ..., n, \tag{6}$$

(where $U_i = \partial U/\partial c_i, F_i = \partial F/\partial c_i - m_i$ etc.)

Second, emission reductions should not be costlier than the benefit from reduced emissions is, neither should they be so undersized that emissions did more harm than reducing them would cost. Therefore the marginal cost of reducing emissions must equal the marginal environmental cost of emissions measured in terms of good i:

$$\frac{-F_v}{F_i} = \frac{E'}{U_i}, \quad i \neq 0. \tag{7}$$

Third, the following defines the relationship between the MRS in consumption and international prices. MRS is adjusted to environmental externalities in other countries from importing goods, as imports increase emissions in the rest of the world. In other words, the ratio of two marginal import costs, adjusted by the terms of trade effects T_i, must equal the externality-adjusted MRS in consumption. This reflects that the ratio of marginal import costs need to equal the ratio marginal utilities of importing those goods, when marginal harm from emissions changes is taken into account:

$$\frac{p_0 + T_0}{p_i + T_i} = \frac{(U_0 - E') - E'e_0}{U_i - E'e_i}, \quad i = 1, ..., \eta, \tag{8}$$

where

$$T_j = \sum_i m_i \frac{\partial p_i}{\partial m_j}, \quad j = 0, 1, ..., \eta.\text{[2]} \tag{9}$$

The terms T_j measure terms of trade effects of the increase in import of good j. The terms of trade effect is here defined as the aggregate monetary cost change of net imports in response to a change in imports of a single good. T_j is positive for imported and negative for exported goods in the simple case where $\partial p_i / \partial m_j = 0$ and $\partial p_j / \partial m_j > 0$ $(i \neq j)$ (importing more good j does not change the international price of i, and importing j increases the price of j itself). In the more general case where changes in net imports of one good may affect the international prices of other goods as well $(\partial p_i / \partial m_j \neq 0)$, this this simple relationship does not hold.

3.1.2 Carbon taxes and tariffs in the model

Next I will explain how Hoel proposed the social optimum to be achieved by implementing carbon taxes and tariffs in a competitive economy.

There is a common carbon tax θ for all users, and import tariffs or export

[2] $\sum_i$ from here on is shorthand of $\sum_{i=0}^{n}$

subsidies t_j for all traded goods:

$$\theta = E' \frac{p_i + t_i}{U_i}, \quad i \neq 0, \tag{10}$$

$$\begin{aligned} t_j = T_j + \theta e_j, \quad &\text{for} \quad j \leq \eta \quad \text{(tradables)}, \\ t_j = 0, \quad &\text{for} \quad j > \eta \quad \text{(non-tradables)}. \end{aligned} \tag{11}$$

E' is the marginal environmental cost measured in utility, while $(p_i + t_i)/U_i$ is dollars per unit utility for good i, after the possible tariff has changed a good's price to $p_i + t_i$. It will be shown below that the carbon tax does not depend on the good i, and carbon tax thus equals the monetary measure of the marginal environmental cost of emissions. The tax internalizes the negative externalities from domestic emissions, but would cause carbon leakage to occur without adoption of carbon tariffs simultaneously.

The import tariff (or export subsidy) changes the price of j to $p_j + t_j$. Positive t_j is an import tariff for imported goods and an export subsidy for exports. T_j measures the terms of trade effect of an increase in imports of the good j, and is defined as in (9). The term θe_j measures the value of a change in foreign emissions as a result of the marginal increase in imports of the good j. As a terms of trade effect T_j, a change in foreign emissions e_j can also be signed either positively or negatively, since importing some goods may decrease emissions abroad in some cases. Therefore the tariff t_j can also be negative, in which case t_j is an import subsidy or an export tax.

It is worth noticing, that for a small country, or a group of countries, the terms of trade effects $(\partial p_i/\partial m_j)$ are close to zero, while the marginal changes in foreign emissions (e_j) may be relatively large. Therefore the level of tariff t_j for good j will only depend on the sign and magnitude of e_j.

Consumers will face the price vector $(p_0 + \theta + t_0, p_1 + t_1, ..., p_n + t_n)$. The carbon tax is included in the price of fossil fuels, and carbon tariffs in the prices of other goods. The optimal consumption vector needs to satisfy

$$\frac{U_0}{U_i} = \frac{p_0 + \theta + t_0}{p_i + t_i}, \quad i = 1, ..., n, \tag{12}$$

which demonstrates that the ratio of marginal utilities from consumption of fossil fuels needs to equal the ratio between prices the consumers face.

When we combine this with (10) and (11) we get

$$\frac{U_0}{U_i} = \frac{p_0 + t_0}{p_i + t_i} + \frac{E'}{U_i}, \quad i = 1, ..., n. \tag{13}$$

which can be written

$$\frac{U_0 - E'}{U_i} = \frac{p_0 + t_0}{p_i + t_i}, \quad i = 1, ..., n. \tag{14}$$

or

$$\frac{p_i + t_i}{U_i} = \frac{p_0 + t_0}{U_0 - E'}, \quad i = 1, ..., n. \tag{15}$$

From this we can see that $(p_i + t_i)/U_i$ does not depend on i (for $i \neq 0$). Therefore it is proven that (10), or the level of the carbon tax is not affected by the choice of good i, but is only determined by the marginal environmental cost.

For given prices and tariffs, producers will maximize their income, considering they need to use fossil fuels as production inputs and pay carbon tax for using them $((p_0 + t_0)x - (p_0 + t_0 + \theta)v + \sum_{i>0}(p_i + t_i)y_i = \sum_i (p_i + t_i)y_i - \theta v)$ subject to the efficiency condition $F(y, v) = 0$. From this follows:

$$\frac{F_0}{F_i} = \frac{p_0 + t_0}{p_i + t_i}, \quad i = 1, ..., n. \tag{16}$$

$$\frac{-F_v}{F_i} = \frac{\theta}{p_i + t_i}, \quad i = 1, ..., n. \tag{17}$$

Which mean that the marginal rate of transformation between fossil fuels and other products must equal the ratio of prices of those products.

We can see that the MRS=MRT condition (6) can be obtained by combining (14) and (16). Therefore (17) can now be written as

$$\frac{-F_v}{F_i} = \frac{E'}{U_i}, \quad i \neq 0, \tag{18}$$

equivalent to (7): marginal cost of reducing emissions must equal marginal environmental cost of emissions.

(10) and (12) give

$$\frac{(U_0 - E') - E'e_0}{U_i - E'e_i} = \frac{(U_0 - E')\left(1 - \frac{\theta e_0}{p_0 + t_0}\right)}{U_i\left(1 - \frac{\theta e_i}{p_i + t_i}\right)}, \tag{19}$$

furthermore, we may insert (11) and (12) into the right hand side to obtain

$$\frac{U_0 - E' - E'e_0}{U_i - E'e_i} = \frac{p_0 + T_0}{p_i + T_i}, \quad \text{for} i = 1, ..., \eta, \tag{20}$$

equivalent to the condition (8)

The results above show that social optimum conditions (6)-(8)derived in the previous subsection can be achieved in the competitive economy with the taxes and tariffs defined in (10) and (11).

3.2 The optimum without tariffs

Hoel also analyzes the situation where the use of tariffs is ruled out. To simplify the case, he assumes that all international prices are fixed, all goods are tradable, and that there is no domestic production of fossil fuels. The only endogenous consumer price in this simplified version of the model is the price of fossil fuels. The vector $\tilde{\mathbf{y}} = (y_1, \ldots, y_n)$ denotes the vector of net outputs for the n non-fuel goods. Whereas vectors for fuel use are $\tilde{\mathbf{v}} = (v_1, \ldots, v_n)$ and $\tilde{\mathbf{c}} = (c_1, \ldots, c_n)$. Thus, the net imports are given by:

$$m_0 = c_0 + \sum_i v_i; \quad m_i = c_i - y_i, \quad \text{for } i > 0.\text{[3]} \tag{21}$$

First part of which denotes the imports of fossil fuels for consumption (c_0) and for production inputs (v_i). Since there is no domestic production of fossil fuels, all of domestic emissions are included in m_0. Foreign emissions are still $e(m_0, m_1, \ldots, m_\eta)$, but in this case government chooses differentiated carbon taxes $(\theta_0, \theta = (\theta_0, \theta_1, \ldots, \theta_n)$ instead of tariffs to maximize welfare. Households face the price vector $(p_0 + \theta_0, p_1 \ldots, p_n)$. The carbon taxes do not affect the prices of products other than fossil fuels themselves, since international prices are fixed and there is no tariffs to create a difference between international and domestic prices. If a domestic producer would try to raise its prices because of the tax, it would simply lose its market share to foreign producers. Thus the indirect utility function is

[3] In this section $\sum_i$ is shorthand for $\sum_{i=1}^{n}$

$$V(\theta_0, I) = \max U(c_0, \mathbf{c})$$
$$\text{subject to} \quad (p_0 + \theta_0)c_0 + \sum_i p_i c_i \leq I \tag{22}$$
$$\text{(where } I \text{ is household income)}$$

Which gives the maximum attainable utility for the consumers, given their income I and the carbon tax on fossil fuel consumption. The limiting condition simply means that total amount of consumption at the given price level, and tax on fuels, cannot exceed the aggregate household income.

The properties of the indirect utility function function V are

$$\frac{\partial V}{\partial c_0} = -c_0 \lambda; \quad \lambda \equiv \frac{\partial V}{\partial I}. \tag{23}$$

This is so called Roy's Identity, which states that the demand for fossil fuels is the ratio between partial derivatives of the indirect utility function.

The profit function defines how firms profits are determined by prices and outputs subtracted by the cost of fossil fuel inputs. The cost of fossil fuels in production includes the international price of the fuel and the differentiated carbon tax:

$$\pi(\theta) = \max \sum_i p_i y_i - \sum_i (p_0 + \theta_i) v_i \tag{24}$$

with the properties

$$\frac{\partial \pi}{\partial \theta_i} = -v_i. \tag{25}$$

I.e. increase in carbon tax for a certain good decreases the use of fossil fuels as a production input for that good. The vector of outputs and fuel inputs (y, v) is constrained by the set of feasible technologies.

The household income I consists of profits and reimbursed taxes. To keep the analysis simple, it is assumed that the carbon tax is distributed entirely to the consumers:

$$I = \pi(\theta) + \theta_0 c_0(\theta_0, I) + \sum_i \theta_i v_i(\theta_i) \tag{26}$$

Following the previous expressions, the welfare W can be written as

$$W = V(\theta_0, I) - E(c_0(\theta_0, I) + \sum_i v_i(\theta) + e(c_0(\theta_0, I) + \sum_i v_i(\theta), c_1(\theta_0, I) - y_1(\theta), ..., c_n(\theta_0, I) - y_n(\theta))) \tag{27}$$

Or, phrased in words, expressed as indirect utility from consumption minus environmental externality determined by domestic use of fossil fuels in consumption and production inputs and net imports.

The optimal level of carbon taxes θ_i to maximize W can be calculated by taking a lagrangian:

$$\begin{aligned} L = V(\theta_0, I) - E(c_0(\theta_0, I) + \sum_i v_i(\theta) \\ +e(c_0(\theta_0, I) + \sum_i v_i(\theta), c_1(\theta_0, I) - y_1(\theta), ..., c_n(\theta_0, I) - y_n(\theta) \\ +\mu[\pi(\theta) + \theta_0 c_0(\theta_0, I) + \sum_i \theta_i v_i(\theta_i) - I] \end{aligned} \tag{28}$$

The first-order conditions are

$$\frac{\partial L}{\partial I} = \lambda - E' \cdot \Big[(1+e_0)\frac{\partial c_0}{\partial I} + \sum_{i>0} e_i \frac{\partial c_i}{\partial I}\Big] + \mu\Big[\theta_0 \frac{\partial c_0}{\partial I} - 1\Big] = 0,$$
$$\frac{\partial L}{\partial \theta_0} = -\lambda c_0 - E' \cdot \Big[(1+e_0)\frac{\partial c_0}{\partial \theta} + \sum_{i>0} e_i \frac{\partial c_i}{\partial \theta_0}\Big] + \mu\Big[c_0 + \theta_0 \frac{\partial c_0}{\partial \theta_0} - 1\Big] = 0, \tag{29}$$
$$\frac{\partial L}{\partial \theta_j} = -E' \cdot \Big[(1+e_0)\sum_i \frac{\partial v_i}{\partial \theta_j} - \sum_i e_i \frac{\partial y_i}{\partial \theta_j}\Big] + \mu + \sum_i \theta_i \frac{\partial v_i}{\partial \theta_j} = 0.$$

By multiplying the first FOC by c_0 and adding it to the second FOC we get

$$-E' \cdot \Big[(1+e_0)\big(\frac{\partial c_0}{\partial \theta_0} + c_0 \frac{\partial c_0}{\partial I}\big) + \sum_{i>0} e_i \big(\frac{c_i}{\partial \theta_0} + c_0 \frac{\partial c_i}{\partial I}\big)\Big] + \mu\theta_0\Big[\frac{\partial c_0}{\partial \theta_0} + c_0 \frac{\partial c_i}{\partial} I\Big] = 0 \tag{30}$$

The compensated demand derivatives for all i are given by

$$\Big(\frac{\partial c_i}{\partial \theta_0}\Big)_{u=\bar{u}} = \frac{\partial c_i}{\partial \theta_0} + c_0 \frac{\partial c_i}{\partial I} \tag{31}$$

When (30) is divided by (31) we get the carbon tax for domestic consumption of fossil fuel:

$$\theta_0 = \frac{E'}{\mu} \cdot \left[1 + e_0 + \frac{\sum_i e_i \Big(\frac{\partial c_i}{\partial \theta_0}\Big)_{u=\bar{u}}}{\Big(\frac{\partial c_0}{\partial \theta_0}\Big)_{u=\bar{u}}}\right] \tag{32}$$

The last FOC can be rewritten as

$$-E' \cdot \Big[(1+e_0)\sum_i \frac{\partial v_i}{\theta_j} - \sum_i e_i \frac{\partial y_i}{\partial \theta_j}\Big] + \mu \frac{\theta_j}{\alpha_j} \sum_i \frac{\partial v_i}{\partial \theta_j} = 0 \tag{33}$$

since α is defined by

$$\alpha_j = \frac{\theta_j \sum_i \frac{\partial v_i}{\partial \theta_j}}{\sum_i \theta_i \frac{\partial v_i}{\partial \theta_j}} \tag{34}$$

dividing (33) by $\sum_i (\partial v_i)/\partial\theta_i)$ we get θ_j that maximizes W:

$$\theta_j = \alpha_j \cdot \frac{E'}{\mu} \cdot \left[1 + e_0 + \frac{\sum_i e_i \left(-\frac{\partial y_i}{\partial \theta_j} \right)}{\sum_i \frac{\partial v_i}{\partial \theta_j}} \right] \tag{35}$$

Coefficient α_j measures the ratio between marginal changes in tax revenues from carbon tax for product j and aggregate carbon taxes from all products (except fossil fuel) from increasing carbon tax for product j.

The term E'/μ in (32) and (35) represents the marginal cost of CO_2 emissions in money terms (marginal environmental cost in terms of utility divided by a hypothetical transfer of money). $1 + e_0$ gives the direct effect of the per unit increase in domestic fuel use on global emissions. Thus $(E'/\mu)(1 + e_0)$ gives the marginal environmental cost of the direct effect of increased domestic fuel use. The last terms of (32) and (35) represent the indirect effects on global emissions resulting from changes in net imports of non-fuel goods.

The nominator in the last term of (32) is the compensated direct price derivative of the demand for fossil fuels, and thus negative. The numerator captures the effect of a compensated increase in the consumption of fuels on foreign emissions.

The nominator in the last terms of (35) measures the change a rise of fuel price in sector j causes in the total fuel input of all sectors. The numerator of the last term is the effect a rise in the price in fuel price in sector j has on foreign emissions. Since this term clearly differs between sectors, θ_j i.e. the optimal carbon tax needs to also differentiate. Unlike in the case with optimal tariffs, the relationship between the sign and size of e_j and the optimal carbon tax for sector j is not straightforward. One can also see by comparing (32) and (35) to (10) and (11) that the amount of information needed to calculate optimal tax levels θ_0 and θ_j is much larger than that needed to calculate the uniform carbon tax and differentiated tariffs.

3.2.1 Summary of the Hoel's model

As we have seen in the previous subsections, Hoel's model shows that carbon taxes ought not to be differentiated between sectors in carbon tariffs can be used. The domestic carbon tax should be equivalent to marginal environmental cost of emissions in monetary terms, while the optimal tariff should be the domestic price of carbon scaled to the marginal change of foreign emissions in response to marginal increase in imports of a good. However, if tariffs cannot be applied, the optimal solution requires differentiation between sectors, even with the simplifications used in that case. Even though calculation of the optimal levels of tariffs requires a large amount of information, the information needed for optimally differentiated taxes is significantly larger. Furthermore, there is no simple relationship between for example fossil fuel intensity and the optimal carbon taxes for different sectors. Therefore, based on Hoel's model, there are no good reasons not to implement carbon tariffs along with the undifferentiated carbon tax. To further demonstrate how the model works, I will provide some examples with numerical approximations for variables. The following calculations should not be taken as accurate, and only provide crude approximations for the sake of an example.

The social cost of a ton of carbon dioxide is usually considered to be between €10 and €50, depending on discount rate (see e.g. Bijgaart, Gerlagh, and Liski, 2016). Iron and steel industry is an example of a sector that would be highly susceptible to carbon leakage. For example Fischer and Fox (2012) estimated the leakage rate (the change in foreign emissions) for iron and steel industry in the OECD countries to be 58 percent without any adjustment policies to mitigate the leakage. Depending on energy source and production method among others, carbon intensity of steel production is around 1-2 tonnes of CO_2 per ton of crude steel (Hasanbeigi et al., 2016). If we assume the emissions embodied in the steel production to be 1.5 tonnes of CO_2 per ton of steel, and the social cost of a ton of carbon to be €25, the carbon tax for a ton of crude steel would be $1.5 * £25 = 37.5$.

For a small country the terms of trade effect would be near zero, since changes in its net imports would not have noticeable effects on international prices. So the calculation of the tariff would not include the terms of trade component. The price of steel on international markets was around €300 in early 2017 (*Trading Economics: Steel* n.d.). By inserting these exemplar numbers into (10), the optimal carbon tariff for a ton of steel would be:

$$t_{steel} = 0 + 37.5 * 0.58 = 21.75. \tag{36}$$

Compared to for example to paper, pulp and print industry which, according to Fischer and Fox (2012), would have leakage rate of 2 percent, steel would have much higher tariff level. Assuming again that the country is small and the terms of trade effect is negligible, a ton of pulp would have the following tariff[4]:

$$t_{pulp} = 0 + 7.5 * 0.02 = 0.15. \tag{37}$$

In percentage terms this would mean around 7 percent tariff for steel imports, and below 0.02 (with the price of pulp aroud €800 per tonne) percent tariff for pulp imports. From these examples we can see that in a small country, the optimal carbon tariffs would be minimal for pulp compared to steel. For a larger country the calculation would change, since the terms of trade component would affect the calculation as changes in imports would affect international prices of goods.

[4]It is assumed that pulp production produces around 0.3 tonnes of CO_2 per ton of pulp (magnitude checked from Vos and Newell, 2009). This equals a carbon tax of €7.5 per tonne.

In the case without tariffs the carbon tax for a ton of steel the calculation would be far more complicated, as it would require estimates about what effects the carbon tax on one sector would have on every sector, in addition to indirect effects on emissions from changes in net imports after the tax would be set.

3.2.2 What is missing in Hoel's model?

Even though Hoel's model provides a strong argument for carbon tariffs as a second-best option in climate policy, there are many possibly significant factors the analysis does not capture. For example, bootstrapping and free-riding effects analyzed by B. R. Copeland and M. S. Taylor (2004) are clearly out of scope of the model, as well as any other technology or policy-making related factors. The coalition that sets the tax and the tariffs is assumed to be exogenously given and fixed, and there are no considerations of the policy response in foreign countries.

Hoel's model optimizes welfare only for the home country. Therefore it does not take into account possible negative effects of tariffs to the rest of the world, and thus the global cost-effectiveness of the policy. This seems to be the main reason, why carbon tariffs are not considered to be very good solution in the global scheme in some studies (Böhringer, J. Carbone, and Rutherford, 2016). Hoel himself argues in the article that any country can avoid the negative effects of the tariffs by joining the cooperating climate coalition. There is a counter-argument for this however: abuse of terms-of-trade effects by carbon tariffs may legitimate manipulation of terms-of-trade effects on the pretext of other issues as well. This argument was raised by Böhringer, Lange, and Rutherford (2014) who decomposed the differentiation efforts similar to Hoel into leakage and terms-of-trade motives.

While Hoel argues that the information needed for optimal tariff design is smaller than that needed for optimal tax design, the amount of data available for practical policy design might anyways be much smaller than the optimal design would require. The data required for truly optimal policy design following the model should include detailed and accurate information on the emission levels of different products in other countries. Furthermore, equal tariff levels for all producers of the same good would not place any incentives for foreign producers to lower their own emissions. However, as Hoel mentioned, these arguments would also apply to carbon price differentiation. Therefore Hoel's model can be considered a basis for policy design. The practical questions about the superiority of tariffs rise from quantitative estimates of whether the benefits from tariffs are significant, and whether tax differentiation and tariffs have large differences in their impacts and in their practical implementation.

4 Studies and results

In this section I will briefly explain how carbon leakage is studied in the economics literature, and review the main results from the studies.

4.1 Background

The basis for most of the estimates for carbon leakage rate has been the allocation of greenhouse gas emission reduction targets determined in the Kyoto Protocol. The economic studies of carbon leakage typically classify countries into two groups: Kyoto Agreement Annex I and non-Annex I countries. Annex I countries are those that should have reduced their greenhouse gas emissions to 1990 levels by 2012. Respectively non-Annex I countries are those without binding targets for emissions in the Kyoto Agreement.

The only major region to place a price on carbon has been the European Union with its Emissions Trading Scheme (ETS). EU has tried to prevent carbon leakage effects by allocating extra allowances to the sectors deemed most vulnerable to it. More about EU ETS in A. D. Ellerman, F. J. Convery, and De Perthuis (2010).

4.2 Computable general equilibrium models

The estimates of carbon leakage are typically based on multi-region multi-sector computable general equilibrium models (CGEs). CGEs use realistic economic data to solve numerically the equilibrium of supply, demand and prices in a set of markets. They are a tool for a kind of semi-empirical analysis that uses mostly empirically gathered data to analyze changes in economy by the microeconomic foundations of Walrasian equilibrium. A CGE model handles the economy as a circular flow of commodities between firms and households, possibly across multiple regions. Factor inputs like labor and capital are used by firms to provide goods and services to households, which in turn supply firms with labor. A multi-region model used in modeling carbon leakage also contains flows of imports and exports between different regions. A CGE solves a set of prices by employing three conditions: market clearance, zero profits and income balance. (Wing, 2004)

In a model an external shock, usually the change in the emissions policy when carbon leakage is studied, changes relative prices, which in turn affects trade flows through price elastic supply and demand. A CGE model can include data from inputs and outputs and combine them with assumptions on market structure and elasticities. A dozen regions can be included in a model. Common primary resources in models are labor, capital and fossil-fuel resources. Figure 1 provides a rough depiction of a circular flow of economy in a CGE model. Fossil fuels can be categorized into oil, coal and gas for example. Production of commodities is captured by constant elasticity of substitution (CES) functions. A model however cannot include all effects in the world that affect carbon leakage, nor can it include all the features of Kyoto Agreement and other international policies to reduce CO_2 emissions. (Böhringer, J. Carbone, and Rutherford, 2016)

As discussed in subsection 2.4, carbon leakage typically consists of two components in these models: non-energy market channel and energy market channel, or terms of trade effect and fuel price effect (Elliott and Fullerton, 2014). The first of these effects provides a competitive edge to producers in non-abating countries depending on demand elasticities of the products. Another one encourages more intensive fuel consumption abroad as international fuel prices fall. The framework is thus typically very similar to the simplified version of Hoel's model. Other effects like more nuanced view on industry relocation and market structures have been included in CGE models by some studies, but in most of the models used by studies, leakage

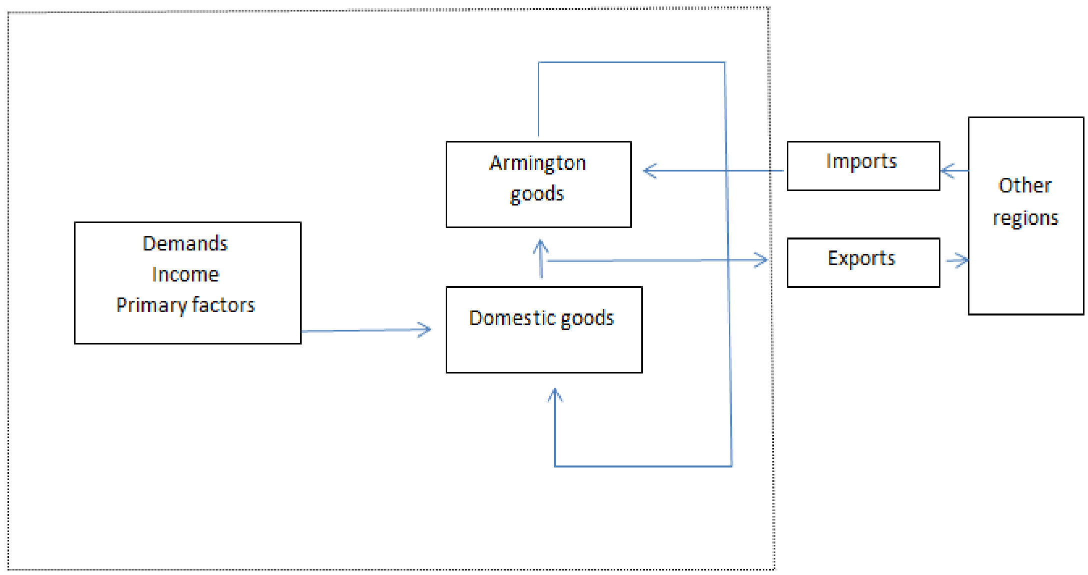

Figure 1:

Figure 2: Flow chart of a CGE model

consists primarily of the two main effects mentioned above.

4.2.1 Main findings of the models

Most estimates indicate the carbon leakage rate to be roughly between 5 and 30 percent, usually below 20 percent, but these results are often highly sensitive to change of assumptions and may change considerably if a new feature is introduced into a model. Burniaux and Joaquim Oliveira Martins (2012) summarized previous estimates of leakage rates associated with the implementation of the Kyoto Protocol in 2000. These estimates ranged from 2% to 21% (Light, Kolstad, and Rutherford, 1999; Bollen, Manders, and Timmer, 1999; M. Babiker, Reilly, and Jacoby, 2000; Manne and Richels, 2000; Burniaux and Martins, 2000). Results may vary from negative leakage to assessing unilateral policies totally counterproductive with leakage of over 100%. Additionally, all the limitations of the CGE models in general apply to these results.

A summary of estimates for carbon leakage in CGE studies is presented in Table 1. The leakage rate presented is the one from researchers' standard scenario, if there is one, or as a range obtained with different plausible assumptions. The different results should not be simply taken as different estimates for the leakage rate universally, but the studies differ by their assumptions, regions involved, timeline and the emissions mitigation schemes they try to assess. The region used in a study is the Annex I countries of the Kyoto Protocol (Nations, n.d.), unless else is mentioned. It is worth noticing that the leakage rate is smaller if the coalition is larger, since there are less countries where emissions can leak to. The numbers are presented rather as descriptions of the estimated magnitude than accurate predictions. The only results show that leakage rate is quite moderate in all other studies but in M. Babiker (2005). Though aggregate rates are modest, certain sectors are estimated to be significantly more susceptible to leakage than others.

Fore example, Paltsev (2001) assesses sectoral and regional determinants of the leakage. He uses a static multi-sector, multi-regional model. Paltsev decomposes the leakage to regional and sectoral level contributions. He finds that the Kyoto Protocol leads to carbon leakage rate of around 10 percent for the baseline values, but higher for chemical and metal industries. However, he also argues that exemptions from carbon taxes of any sector are no justified because they would lower the welfare based on his model. In Paltsev's model degree of regional and sectoral data disaggregation or international capital mobility do not change the rate of leakage significantly.

As the outlier among the estimates, M. Babiker (2005) finds two sources that may strongly contribute to offshore production and carbon leakage effect: the pro-competitive effect of carbon abatement policies in initially monopolized industries and the effect of entry and exit of firms in such industries. He uses a seven-commodity, seven-region applied general equilibrium model to model strategic interaction between energy-intensive companies through spatial Cournot oligopolies with free entry and exit to capture these effects. The locational effects in Babiker's model are small with differentiated (Armington assumption) products and larger with homogenous products (Heckscher-Ohlin case). The difference between the assumptions is substantial: e.g. the fall in number of firms in OECD is 2% or 53.3% depending on the assumption. With Heckscher-Ohlin assumptions and increasing returns to scale carbon leakage in this model can be over 100%. Previous studies had found the carbon leakage rate resulting from Kyoto Protocol like policy to be between 5% and 25%. Babiker argues in his study that if industry relocation with economies of scale, market power and richer representation of international trade is taken into the model, the scope of carbon leakage might be much larger. (M. Babiker, 2005)

Gerlagh and Kuik (2007) added the possibility of international technology spillovers to a large CGE model. Abatement policies may change the direction of technological country both domestically and internationally. These developments in environmental technologies may diffuse to non-abatement countries. The authors found that even modest level of technological spillovers may reduce the leakage from the baseline estimate of 17 percent significantly, and lead to even negative leakage rates.

Different studies have analyzed effects of regulation in different regions of the world. The leakage rate is not the same for different regions. Böhringer, Lange, and Rutherford (2014) estimated the leakage rate for the EU to be over 35 percent, while the estimate for the United States was only slightly over 15 percent. There are couple of reasons for this. First, the EU is relatively more open economy, its exports and imports constitute a larger share of the economy in the EU than in the US. This is specifically the case for emission-intensive goods and fossil fuels. The EU is a major net exporter of energy-intensive goods, while it imports a large share of fossil fuels it consumes. Additionally, EU's emission-intensive industries are relatively less emission-intensive than those of the US. This causes a larger per production-unit increase in global emissions if production moves away from the EU.

There are plenty of uncertainties in the results of the models; they may be sensitive to uncertainties in estimates of certain paramaters, and a CGE model cannot capture all of the factors involved. The leakage rate is not probably linear in relation to the emission reduction target. Lowering GHG emissions may become more expensive when the reduction target is tightened. Therefore the leakage rate may be higher with tighter reduction targets than those used in the studies.

Study	Estimate of leakage in base scenario	Notes
M. Babiker, Reilly, and Jacoby, 2000	6%	
M. Babiker, 2005	30% to 130%	Includes industry relocation effects. In higher estimates fuels assumed to be Heckscher-Ohlin goods
Bernard and Vielle, 2009	Below 1%	Assesses EU's "Energy-Climate" directive
Bollen, Manders, and Timmer, 1999	9% to 24%	Increases over time
Burniaux and Martins, 2000	2%	
Burniaux and Joaquim Oliveira Martins, 2012	2% to 4%	
Elliott, Foster, et al., 2010	20%	
Gerlagh and Kuik, 2007	-16% to 17%	Technology spillovers added
Ho, Morgenstern, and Shih, 2008	26%	Assesses a unilateral policy by the US
Light, Kolstad, and Rutherford, 1999	20%	
Kuik and Hofkes, 2010	11%	Assesses the EU ETS
Manne and Richels, 2000	10% to 15%	
Oliveira-Martins, Burniaux, and J. P. Martin, 1992	1% to 16%	
Paltsev, 2001	10%	

Table 1: Estimates of leakage rate in CGE studies

4.3 Key parameters

As I mentioned before, the results from CGE models can be very sensitive to certain assumptions. In this subsection I will explore which are the most important parameters in the models for the results regarding leakage rate. A major choice in assumptions discussed in literature is whether goods are considered Heckscher-Ohlin (H-O) goods or Armington goods. To put it simply, the important distinction between the two is that with H-O goods produced in different countries are homogeneous, whereas Armington goods are differentiated, i.e. they are not perfect substitutes to each others.

Burniaux and Joaquim Oliveira Martins (2012) provide sensitivity analysis to assess how leakage rates react to changes in parameter values. The authors find in their analysis that the key parameter in the results obtained by the GREEN model they employed is the supply elasticity of coal. With high supply elasticity leakage rates are quite low and stable, but with low elasticity leakage rates can be very high (40%). In practice this means that the leakage can get high if supply of coal does not respond to lower prices caused by carbon regulation. Totally inelastic supply of fossil fuels would make the reduction of emissions impossible, since all the fuel would simply be consumed elsewhere when its price would drop.

They also find that product substitution in non-energy markets has a quite small impact on leakage rates, so choice between Heckscher-Ohlin and Armington assumptions is not significant in explaining differences between models. The impact of capital mobility is also small: for moderate values of Armington elasticity, abatement in Annex 1 countries induces a current account surplus through lower energy imports, which again results in real exchange rate appreciation and inflow of capital. Only for high values of Armington elasticity there may be small real exchange rate deterioration. (Burniaux and Joaquim Oliveira Martins, 2012)

The authors' findings suggest that the elasticity of coal supply plays a critical role in determining carbon leakage, while oil supply elasticity plays only a minor role. With elastic coal supply, coal markets' integration plays a minor role, but with less elastic supply, leakage rates may rise high (60%) if coal markets are integrated. However, this result would include huge shifts in coal exports, which is probably unrealistic. International capital mobility and differentiation of final goods play less significant roles. They also argue that the shape of production function is important in this matter. When possibilities for inter-fuel and/or inter-factor substitution are greater than previously reported in the literature, leakage rates may be high. According to the authors, there is little empirical evidence concerning supply elasticity of carbon, for which their results are highly sensitive. The few empirical estimates are quite mixed as well: for example, Beck, Jolly, and Loncar (1991) estimated the aggregate elasticity to be quite low: from 0.4 in the short term to 1.9 in the long run, whereas Mellish (1998) estimated it to be high, around 7. (Burniaux and Joaquim Oliveira Martins, 2012)

Since the elasticity of coal supply is deemed to be the key parameter in assessing the magnitude of carbon leakage, the structure of international coal markets plays a significant role. Light, Kolstad, and Rutherford (1999) argued that assumption of regional differentiation may lead to underestimation of the potential leakage effects. If coal markets are highly integrated and the supply elasticity is low, leakage rate might be higher than most of the estimates indicate. However, this development could be prevented by setting a tax on coal exports.

M. Babiker (2005) states that leakage rate can reach very high level if energy-intensive goods are modeled as Heckscher-Ohlin goods, and company entry and exit -effects are taken into account. He argued that it is reasonable to assume that energy-intensive goods will eventually transform into homogenic goods, at least in the long run. This is an assumption not shared, at least in the time horizon of the models, by most other scholars. M. Babiker also finds two sources that may strongly contribute to offshore production and carbon leakage effect: the pro-competitive effect of carbon abatement policies in initially monopolized industries and the effect of entry and exit of firms in such industries.

In conclusion, elasticity of coal supply and integration of integration of the international coal markets are the main parameters that have really large effects on the overall estimates of carbon leakage in CGE models. Other parameters, like Armington elasticites and production sunstitutions play a smaller role, but contribute to the variance between results. However, there are other factors that these models ignore, but might be important for the leakage rate in reality.

4.4 Findings from analytical models

In addition to "large" CGE models that try to model effects in the world economy with large amounts of data used as variables, mechanisms of carbon leakage have been studied with simplified GE models to assess more particular attributes of the effects and parameters often ignored by the larger CGEs. I will present a short review of different insights these "smaller" models have contributed to the discussion about carbon leakage.

B. Copeland and M. Taylor (2005) decompose a country's best response in a general equilibrium model into three components: free-riding effect, carbon leakage (a substitution effect in their context) and an income effect. They show that although in the case of closed economies home and rest-of-the-world emissions are strategic substitutes, under free trade they may be strategic complements. In other words, unilateral emission reductions in one group of countries may create self-interested reductions in others as well. The authors also show that unlike in autarky, under free trade of goods rigid emission reduction rules can create globally efficient abatement of emissions. Their third result is that pollution permit trade across countries may create unintended consequences through their effects on goods prices. According to the authors, previous models had included a detailed model of the energy sector but almost ignored the role of international trade.

While most models measuring carbon leakage assume the development of technology as constant, Di Maria and Van der Werf (2008) analyze the leakage in a setting where the price on carbon increases incentives to develop clean technologies. They showed that when the development of technology is directed via carbon pricing, leakage rates might be lower. The effect is strengthened, if the elasticity of demand for carbon-based technology is high. In other words, if demand for carbon-based technologies falls significantly when the clean techniques become relatively cheaper, it might be profitable to lower emissions even in non-regulated regions.

Fullerton, Karney, and Baylis (2011)) proposed a Abatement Resource Effect implemented later in CIM-EARTH global multi-region general equilibrium model by Elliott and Fullerton (2014). As described in chapter 2, adaptation to carbon regulation may draw factors of production away from the carbon-intensive sectors and regions. This depends on how easily the economy can shift away from the carbon-intensive production and, on the other hand away from the regulated sectors or regions. They found that the negative leakage depends on the ability of consumers to change into untaxed goods and the ability of firms to substitute emissions into labor or capital. In typical CGE setting ARE cannot occur since labor and capital are assumed to be immobile across regions and thus taxed firms cannot draw resources from untaxed sectors. J. C. Carbone, 2013 also added ARE to an applied general equilibrium model and found aggregate carbon leakage rates of around zero to twenty percent, depending on fuel supply elasticities and substitution elasticities between fossil fuels, and substitution elasticities between capital and labor, and energy goods.

4.5 Empirical evidence?

There does not seem to have been empirical efforts to assess the magnitude of carbon leakage. This is partly because it is extremely difficult to build a sound econometric research setting, but also because not many large-scale unilateral policies have been adopted this far. European Union's emissions trading scheme (EU ETS) is probably the only large enough measure to be studied. The few empirical studies (Reinaud, 2008, F. Convery, D. Ellerman, and De Perthuis, 2008) did not find effects on imports in aluminium or cement industries from the first phase (2005-2007) of the EU ETS. Similar results were obtained by Branger, Quirion, and Chevallier, 2013 in their time-series analysis. However, these results are quite limited as those industries that are most prone to carbon leakage have been protected by allocating them larger share of free permits. Additionally, the price of emission permits has been quite low in the EU ETS this far, so the potential for carbon leakage has not been that large.

Some empirical studies have been made of the Pollution Haven Hypothesis concerning other pollutants. For example Cherniwchan (2017) found significant effects on the emissions of three common pollutants in US factories, particulate matter, lead and toxic chemicals, as a result of NAFTA agreement between the USA, Mexico and Canada. It is doubtful that these results can be generalized to CO_2 emissions though.

Dechezleprı et al. (2014) studied in their recent paper the impact of EU ETS on the geographical distribution of carbon emissions within multinational companies. They found no evidence that the ETS would have caused displacement of emissions from Europe to the rest of the world. They used the data from the Carbon Disclosure Project (CDP) and compared growth rates of multinational companies' EU and non-EU emissions, and examined firm-level changes in the share of emissions within the EU. Neither of these estimates provided any evidence that there would have been any relocation effects as a result of the EU ETS.

5 Policy lessons to be drawn?

In this section I will review what policy measures have been proposed to prevent carbon leakage, how they are assessed in the literature, and how they relate to Hoel's model presented in chapter 3.

5.1 Possible policies to mitigate carbon leakage

There are, broadly speaking, two main categories of carbon leakage prevention measures: Border Tax (or Carbon) Adjustments (BTAs, or BCAs) and domestic carbon price differentiation. Hoel's model covered both of them on general level. BTAs include any kinds of adjustments made on prices of imports and/or exports on the border, like import taxes or export rebates. Carbon price differentiation may be implemented for example by differentiating carbon taxes, as in Hoel's case, or by allocating free emission permits, as is the case within EU ETS. Based solely on Hoel's (1996) model, one could easily argue that an undifferentiated carbon tax combined with differentiated carbon tariffs would be the perfect solution for unilateral climate policy in absence of global regulation. Hoel's assertion has got some support from a numerical model by M. H. Babiker and Rutherford, 2005, which confirmed the result that border taxes should be preferred over sectoral exemptions. However, in practice adoption of carbon tariffs would not be that simple, and there has been some counter-arguments against tariffs in the literature.

BTAs are the most often proposed solution to prevent carbon leakage, as a second-best alternative for climate change policy after global price for GHG emissions (e.g. Paltsev, 2001). BCAs can include border taxes or tariffs, export or import subsidies, mandatory emissions allowance purchases for importers, or embedded carbon product standards. A BTA can embody the full emission externality of an import/export, in this case it is called Full Border Adjustment (FBA). In addition to leveling the competition between domestic and foreign producers, tariffs could also lower industry relocation, as outsourced production could not avoid carbon regulation if it is going to be imported to the original home country.

As discussed in the theory chapter, Hoel (1996) showed in his article, when optimal export and import tariffs can be used, carbon taxes should not be differentiated across sectors. But also that differentiation is an optimal policy if tariffs cannot be implemented. Hoel does not find a good reason to rule out use of tariffs. Although information needed to define optimal levels of tariffs is large, it would be even larger for calculation of optimally differentiated carbon taxes.

Domestic differentiation in pricing of carbon is in Hoel's model and more broadly in literature the third-best solution, mostly considered because tariffs and other BTAs are not practically adoptable. In reality, differentiation of some sort has been the main tool in leakage prevention. Even though it has not been implemented by directly differentiating the price of carbon, but by handing out free emission permits, as in the EU ETS and New Zealand's and California's cap-and-trade systems. There are also differences in how free allocations have been distributed: in the EU ETS that has been done based on capacity, while in California and New Zealand the basis has been output (Meunier, Ponssard, and Quirion, 2014).

A common issue with all differentiation of carbon pricing is that the terms-of-trade motive encourages countries to increase taxation for energy-intensive goods that are exported, and decrease them for the dirty goods that are imported. If the regulating countries are compelled to compensate the negative terms-of-trade effects to other countries, unilateral abatement becomes much costlier for the regulating countries. So there is evidence that tariffs may be less cost-effective solution than plain carbon pricing, if global cost-effectiveness is considered. (Böhringer, Lange, and Rutherford, 2014)

5.2 Evidence on border adjustments

A CGE analysis by Böhringer et al. suggests that while adoption of embodied carbon tariffs (meaning the taxation of carbon emissions is embodied in imported goods) would make global climate policy slightly more effective, a much larger effect would be shift in the cost burden from OECD countries to developing world. The authors claim that justification for carbon tariffs as a global policy option is poor, but that for OECD countries it might appear as an attractive option to mitigate their own costs. So, from a global income distribution point of view, the tariffs would be a poor policy choice. This view was also supported by a meta-analysis of BCAs in CGE models by Böhringer, Balistreri, and Rutherford (2012). The explanation for poor cost-effectiveness increases from BCAs was that tariffs applied at the industry-average levels of emissions do not incentivize individual foreign producers to mitigate their emissions in any remarkable way. (Böhringer, J. Carbone, and Rutherford, 2016)

The authors (Böhringer, J. Carbone, and Rutherford, 2016) also argue that levying the tariff on the full carbon content of traded goods would decrease the cost effectiveness of the global emission reductions. This would happen because the producers would re-route the carbon-intensive production to other markets. They use the optimal tariff design introduced by Hoel (1996), and discussed in the theory section of this thesis, as a second scenario to assess carbon tariffs with their CGE model. In addition to Hoel's design and the fully embodied carbon tariffs, they also studied the effects of two less comprehensive tariff designs: one with only direct emissions included, and another with direct emissions and electricity input. They found that these simpler designs would capture most of the benefits of Hoel's design. All three designs with less than fully embodied carbon reduced leakage significantly less than fully embodied tariffs, while their cost-effectiveness was substantially stronger.

Fischer and Fox (2012) compared four different types of policies that could prevent degradation of competitiveness as a result of carbon pricing by employing a two-good, two-country, partial equilibrium model. The policy measures analyzed were border charges on imports, border rebates for exports, full border adjustments, and domestic output-based rebating (OBR). They found none of these policies was effective to enhance the integrity of global climate policies, so according to this analysis, leakage prevention measures would not do much from the environmental point of view, but would mostly work as a tool to ensure competitiveness (measured by domestic production and net exports) of domestic industries.

The authors' analytical model itself provides little understanding on which policies would be most effective in practice. The import tax will be more effective than export rebate if the net emissions reductions from fewer imports exceed the net emissions displacement by additional exports caused by the rebates. Full border adjustment dominates these both if they are both effective in themselves. If one is ineffective, the other is more effective than the full adjustment. Output-based rebate on the other hand is effective if the displaced foreign emissions are larger than the additional home emissions. It is more effective than full border adjustment if the change in home emissions is larger than the change in different import levels.

When the authors (Fischer and Fox, 2012) used a CGE model to parametrize their analytical model, and study the effects of different policies sector by sector, they found that FBAs are most effective in avoiding net export losses, whereas OBR is usually the most effective to avoid production losses. These results are sensitive to policy assumptions and underlying parameters however. They also found that the model would give different recommendations for different regions of the world. Overall, the authors propose that the FBAs would be the most effective policy in most cases, but OBRs would have higher compatibility with the international trade law while maintaining most of the benefits of the FBAs.

McKibbin and Wilcoxen (2009) also examine border taxes by a detailed

CGE model. Their result suggest that, for the largest part of the economy, border adjustments would be very small, and would not remarkably affect carbon leakage, nor do much to protect domestic industries. The small leakage reductions would be offset by weakened economy in the global level, since international trade would be negatively affected. For some particularly exposed sectors like aluminium, the adjustments would be significant, but in the large scale, McKibbin and Wilcoxen expect administrative complexity and trade obstruction to offset the small benefits border adjustments could have.

Fowlie, Reguant, and Ryan (2016) explored industry dynamics of cement markets for four different policy designs: permit auctioning, grandfathering (allocation of permits based on historic emissions or other predetermined criteria), dynamic allocation updating (allocation of permits based on output in the previous period), and border tax adjustments. Since cement industry is one of the largest sources of GHG emissions, and often highly concentrated, it is an important case to study. The authors argued that it is difficult to predict effects of climate change policies on highly concentrated and emission intensive sectors, such as cement industry. In addition to the problem of carbon leakage, tight regulations may cause problems with the use of market power by some companies. A policy that fully internalizes the externality is not necessarily optimal if the policy distorts competition even more in an already concentrated industry. The specific policy implementation and assumed social cost of carbon heavily affect which policy choice is the most suitable one. If the social cost of carbon is assumed low (below $40), market based solutions where domestic producers fully internalize emission externalities would reduce domestic economic surplus more than emission reductions would increase welfare. In these cases, a combination of emission penalty and production incentives would produce a better outcome domestically. When carbon leakage is taken into account, BTAs are clearly the most cost-effective way to reduce emissions from the point of domestic welfare, but Fowlie et al. also point out that there might be practical barriers regarding their implementation.

Helm, Hepburn, and Ruta (2012) argue from a game theory perspective that BCAs could act as a catalyst to boost the international climate policy development. A BCA on a certain energy-intensive sector could put pressure on other countries to adopt their own carbon pricing schemes and/or BCAs. This could eventually lead to a sectoral agreement about carbon prices on an international level. The sectoral agreement on one sector could in turn encourage policy focus to next sectors where significant gains could be achieved.

Kuik and Hofkes (2010) studied the impacts of possible border adjustments set to mitigate leakage effects of the EU ETS in a multi-region CGE model. Specifically, they concentrated on the sectoral contributions of steel and minerals industries. They found that border adjustments would reduce the leakage rate rather significantly in the steel sector, but the effects would be minor in the minerals sector. The reduction in the overall rate of leakage would be quite modest as well. The authors thus suggest that the border adjustments would not be effective from an environmental point of view, but could be justified as measures to retain competitiveness of certain industries. The two BTA designs applied in the study were both ones with fully embodied direct emissions. One was based on the emission levels of products in the EU, and the another on the emission levels in the exporting country. The design based on the foreign emissions was more effective in preventing leakage than the more practical one based on emissions in domestic EU production.

A study by Antimiani et al. (2013) compared BTAs with different bases and aims (carbon content, competitiveness and leakage prevention) with a CGE model. The result was that BTAs' effect on global emissions is minimal, and on leakage rate quite limited. An outcome quite similar to Böhringer, J. Carbone, and Rutherford (2016). A cooperative scenario where all countries would engage in limiting emissions would be superior to all border adjustment options. In their model it was impossible to set a tariff that would completely eliminate the leakage, since no tariff could prevent the fall in fossil energy prices following unilateral emission reductions.

In conclusion, the literature seems to indicate that while both border adjustments and domestic carbon price differentiation reduce leakage, they do it mainly by enhancing competitiveness of regulating regions at the expense of developing countries. The policy measures assessed do not seem to enhance the cost-effectiveness of climate policies. Thus the argument that carbon tariffs or other measures are necessary to ensure effectiveness of global CO_2 reductions is not supported by the literature. In protecting competitiveness of domestic industries they probably are effective in certain especially vulnerable sectors, they would be effective. These results are naturally dependent on whether the scale of carbon leakage itself is correctly estimated by the models.

5.3 Current policies?

The European Union Emissions Trading Scheme (EU ETS) is the first and largest regional cap-and-trade system for GHG emissions. The leakage within EU ETS was first addressed by giving industries generous amounts of free emission allowances. In the current phase (2013-2020) the amount of free allowances will be gradually reduced. However, more than 75 percent of the regulated emissions in manufacturing are exempted from this transition phase. The criteria for an exemption consist of two measures: carbon intensity of value added and trade exposure. (R. Martin, Muûls, Preux, et al., 2014)

The benefits of output-based allocations used by the New Zealand and California, according to Meunier, Ponssard, and Quirion (2014) are that they retain abatement incentives, and that they level the competition between domestic and foreign producers, as the perceived cost of home production is reduced. However, they might lead to overconsumption of the products in the allocation scheme, since price for consumers will be lower. Subsidies on capacity, exercised by the EU, on the other hand can be beneficial, if the goal is to discriminate between demand states. A capacity subsidy is effective in reducing leakage if leakage occurs when demand is large and new capacity defines where production increases. This may be true for some energy-intensive and trade-exposed sectors with long planning horizons. Allocation based on capacity does not lead to overconsumption through its direct effects on marginal costs of production, but may rather lead to excess capacity, and therefore a decrease in consumer prices through increased supply. The problem in EU-wide uniform policy designs is the differences in vulnerability to leakage between different regions. An optimal policy in one part of Europe may lead to remarkable undeserved profits for companies in another part of the region. Output-based subsidies might be the best solution in some countries, and capacity-based allocations in others.

Meunier, Ponssard, and Quirion (2014) compared the output-based allocations used by California and New Zealand with the free allowance strategy used in the EU ETS. The findings from their analytical model suggested that the output-based allocation, or a combination of output- and capacity-based systems would be more effective than the current system in the level of EU. The current policy in the EU ETS will induce a welfare loss of around 5% compared to an optimal policy, the results even suggest that the current policy may be worse than no policy at all in cement sector.

R. Martin, Muûls, De Preux, et al. (2014) studied compensation rules of EU ETS by applying to it a fundamental economic logic where payments distributed to firms should equalize marginal relocation probabilities weighted by the damage caused by relocation in order to achieve efficiency. They found that the practice in EU ETS results in significant overcompensation for given carbon leakage risk. A far smaller amount of free allowances could be handed out while keeping a similar risk of aggregate relocation.

R. Martin, Muûls, Preux, et al. (2014) also measured the carbon leakage risk by assessing the leakage risk on firm-level. The firm-level risk was evaluated on basis of around 400 interviews with managers of manufacturing companies within the EU ETS. Based on this method, the authors concluded the leakage risk to strongly correlated to carbon intensity, but not to trade-exposure. Therefore the authors argue that free permit allocations to firms that are exposed to trade, but not highly carbon intensive, is too lax in the current scheme.

All these results, together with the evidence on border adjustments, point to the direction that the policy measures to prevent carbon leakage within the EU ETS have been oversized and suboptimal this far. Free allocations are really effective only in the few most vulnerable sectors, and even there they could be more efficiently designed.

6 Discussion and conclusions

Even though many scholars argue in favor of carefully designed carbon tariffs or other types of border tax adjustments against current policies of free allocations and tax rebates, the current evidence of the possible effects of tariffs policies raises questions. Tariffs would probably be a good way to ensure competitiveness of domestic industries, but from a more global point of view their cost-effectiveness is questionable. They could easily be seen as a tool to shift the burden of climate policies from developed to developing world. That might trigger unwanted responses in other countries' trade policies, which could lead to protectionism on pretext of other issues as well. On the other hand, border measures could put more pressure on other regions to adopt their own emissions regulations.

Compatibility with the rules of the World Trade Organization (WTO) and other trade agreements is doubful as well. Additionally, the Kyoto Protocol states that adverse economic effects to developing countries through terms-of-trade effects should be minimized (United Nations, 1997). The rules of the WTO allow exceptions to use trade barriers if it is necessary for the environment (World Trade Organization, 1994), but since the terms-of-trade motive, according to analysis by Böhringer, Lange, and Rutherford (2014) for example, is more significant element of the tariffs than their emissions reductions. Taking the terms of trade effect into account when setting the tariff level - as in the Hoel's model - would be advisable if the goal is to maximize domestic welfare. But if global cost-effectiveness is the main target, the use of tariffs or other border adjustments does not seem to provide very good results. The same issues are present to some extent with tax differentiation and free permit allocations as well, but at least this far they have been deemed more practical politically.

Setting correct levels of tariffs or exemptions has been an issue, and will be in future. Calculation of optimal tariffs on firm-specific level will certainly be too difficult to perform, so the tariffs and other measures have to be defined by country-averages or through some other simplified means. This will eliminate incentives by companies to adopt their own practices to reduce emissions. So-called demand-side leakage could be a problem too: countries could find alternative unregulated markets in which to sell their carbon-intensive products as a result of changes in relative prices (B. R. Copeland and M. S. Taylor, 2004).

Even though Hoel, 1996 argued that there is no good reasons to implement tax differentiation instead of tariffs, based on the literature, it seems plausible to argue that sub-optimal price differentiation can reach most of the benefits of the tariffs while being easier to implement. The information needed for optimal taxes might be much larger than the information needed for optimal tariffs as Hoel shows. However, the information needed for good-enough price differentiation (that retain majority of the benefits of the optimal policy) is not necessarily that much larger than "good enough" tariff differentiation. This does not mean that the current policies implemented by Finland and the EU are close to optimal. Studies suggest that since free allowances and energy tax rebates are currently handed out quite generously, they probably contradict the goals of climate policies while doing little to enhance competitiveness of domestic industries. While allocation of free allowances will probably be tightened in the near future, too lax emission controls in the present may be a problem especially if the Green Paradox is a real issue. Significant industry relocation effects suggested especially by M. Babiker (2005) are certainly a valid concern partially ignored by studies. Their time horizon however, as well as that of some other longer-run effects, may be a reason not to put too much weight on that uncertainty. Climate policy can never achieve its goals in time, if accurate information is required in advance for all longer-run effects.

As an overall conclusion from the results presented in this thesis, carbon leakage is probably a tolerable problem for the economy as whole, though there are large uncertainties in the estimates, as they are based mostly on computable models, not on direct empirical data. The most vulnerable sectors probably need some protection in form of tariffs or carbon price differentiation of some sort. It can be argued that despite recommendations by Hoel's theoretical model, quantitative models imply that there are not necessarily massive disadvantages in regulation exemptions or tax differentiation compared to carbon tariffs. Tariffs would be better from the domestic point of view, but acceptable results can probably be achieved via differentiation as well. The key issue whether protective measures should be adopted at all, is whether the focus should be in domestic welfare gains or global cost-effectiveness of climate policy. The specific policy measures in use by the EU and by Finland do not seem to be optimal, but problems with policy design might rise if tariffs were adopted as well.

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